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Knee-Joint Motion Derived Energy Harvester using Piezoelectric Bimorph

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ABSTRACT

Based on human motion, the knee joint has been selected as part of the energy harvesting device since it shows the high possibility to generate energy from its large motion. This work mainly uses the piezo ceramic bimorph cantilever as the energy harvesting sensor and the N35 MAGNET (3mm x 3mm x 3mm) for the magnetic plucking mechanism. Technique of magnetic plucking has been selected to overcome the low human frequency motion. Force from the magnet acting on the bimorph causing the bimorph to vibrate and then generate electricity. Two categories of magnet are used which consist of primary and secondary magnets. The primary magnet (PM) is mounted on the outer ring and the secondary magnet is fixed on the bimorphs. A prototype has been developed and later examined its performance. Power management module which is integrated circuit is used in managing the harvested energy from the bimorph. The modules consist of RC circuit to convert AC voltage to DC voltage and stepper motor controller to do demonstration of knee joint motion. The highest power successfully harvested from the prototype is 1.596 mW at the speed of 0.386 m/s and 115° angle of knee flexion.

1. Introduction

Energy harvesting is the process of collecting the wasted energy from the surrounding such as heat, sound, vibration and the other sources to generate electricity [1-3]. Nowadays, most electronic devices use portable batteries as power sources. The problem is the portable batteries are not long-lasting and require a high cost for replacement. Modern drive towards mobility and wireless devices motivates intensive research in energy harvesting technologies [4-6]. To reduce the battery burden of people, researchers are investigating a lot of energy harvester devices for the future advancement of power sources. This paper is investigating the possibility of scavenging energy from the human motion by using the piezoelectric bimorph cantilever implemented at the human body specifically on the knee joint. Human motion, be it tilted, inertial or relative motion of two parts, is typically rather slow in comparison to the speeds required by the capabilities of the piezoelectric transducer [7-9]. Due to the low frequency human motion usually in few hertz, it has become a limitation to the piezoelectric energy harvester to perform the generation of electrical energy. This is because the piezoelectric cantilever only operates at its maximum efficiency when actuated at its resonance frequency. The range of its resonance frequency is about ten to thousands of hertz. As a solution for that problem, researchers came up with an idea of frequency up conversion. This is typically implemented via impact or plucking. For this study, to provide the vibration to the piezoelectric bimorph, magnetic plucking mechanism is used. Magnetic plucking technique is the strategy to carry out the frequency up conversion [10-13]. The force from the magnet acting on the bimorph will make the bimorph bend and vibrate freely after the applied force passes through. By using the magnetic plucking technique, high vibration frequency can be achieved.

The knee joint is the best part for implementing this energy harvester. The knee flexion for the normal walking gait cycle is about 60°. The motion of the knee is almost consistent based on the activities carried out by the human. In the military field, soldiers walking for a long distance can use this energy harvester to provide consistent power sources. Waste energy from their motion will be converted to electrical energy and then used to power up the low power devices.

In other work related to this study, a prototype of the knee joint energy harvester has been developed by using the concept of mechanical plucking [14-15]. The plectra were used to pluck the piezoelectric bimorph cantilevers. However, this technique shows limitations when the effect of mechanical plucking damaging the structure of the bimorph. Besides that, direct contact of the plectra produces considerable noise. In [3], they had developed piezoelectric knee-joint energy harvester through magnetic plucking mechanism. The concept of piezoelectric material is converting mechanical energy into electrical energy. From the ambient vibration, piezoelectric material having the mechanical stress and then polarized to generate piezoelectric effect [16-17]. This effect occurs in both monocrystalline material and the polycrystalline ferroelectric ceramic.

2. Methodology

There are four main parts in developing the harvester device which are the input source, magnetic mechanism, power management module and the output. Based on Figure 1, eight pieces of bimorph have been used as energy sensors. All the bimorph individually connected to the rectifier and then are combined in parallel connection.

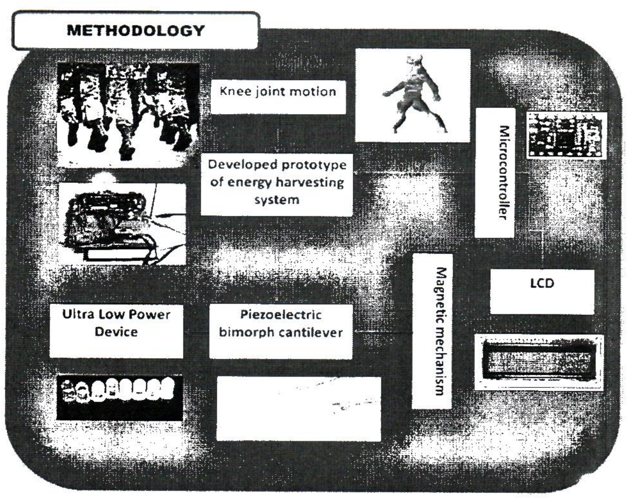

Fig. 1: Block diagram of energy harvesting from knee-joint motion

2.1. *Magnetic Plucking Mechanism*

Vibration of the bimorph cantilever produces electrical energy. The function of the N35 Neodymium (3mm x 3mm x 3mm) magnet is to provide the magnetic force to pluck the bimorph. Based on Figure 2, when the primary magnet moves from position PO to P2, the cantilever will deflect from position R0 to R1 because of the repulsive force between the secondary magnet and the primary magnet. Then, the cantilever releases and vibrates freely to its resonance frequency when Primary Magnet (PM) rotate and passes the Secondary Magnet (SM). The gap between the magnets affected the capability of plucking between them. If the gap is large enough, plucking forces can diminish to zero. The best gap between the magnets are about 1.5 mm according to the previous study.

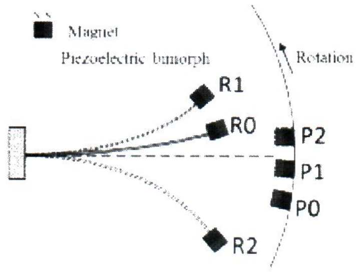

Fig. 2: Magnetic plucking mechanism

2.2. Stepper motor controller and RC circuit

The stepper motor controller circuit has been constructed as shown in Figure 3 to demonstrate the angle of knee flexion with adjustable speed. In this experimental setup, four types of speed were used which are 0.237m/s, 0.282m/s, 0.334m/s and 0.386 m/s. Angle of human knee flexion is different based on the human activities [18]. Range of motion at the knee joint with different movement is shown in Table 1.

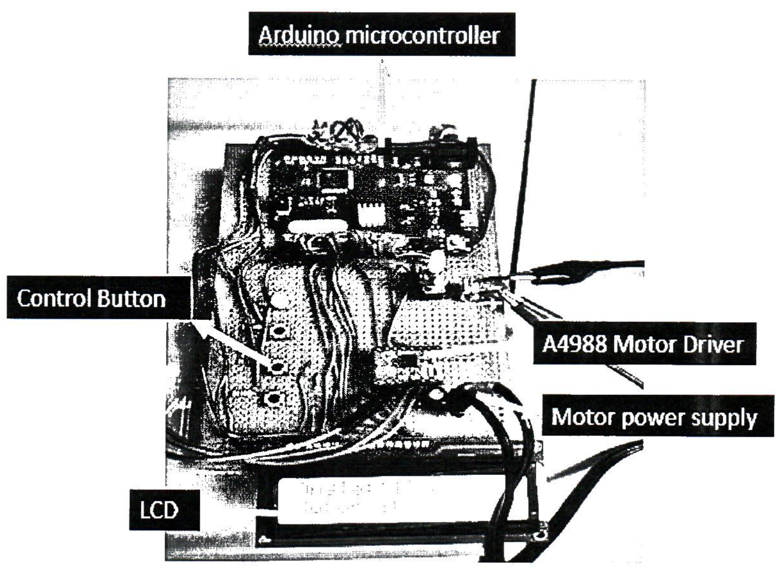

Fig. 3: Stepper motor 17A control circuit for knee movement

Table 1
Angle of knee flexion for different human activities

Activities	Knee Flexion
Walking	60°
Stair climbing	80°
Sitting/rising chair	90°
Running	>115°
Descending stair	85°

2.3. *RC Circuit*

A rectifier circuit is used in this study to convert the generated AC voltage from the piezoelectric bimorph to the DC voltage. Eight number of full-wave bridge rectifier modules are installed individually connected to each piezoelectric bimorph. After that, all the rectifiers are connected either in series or parallel to investigate the best output power can be produced. The output of the RC circuit is connected directly to the multimeter to measure output voltage and current. Besides that, some LED also were used to show the presence of current and to observe the stability of that current.

2.4. *Prototype of the knee joint energy harvester*

Parts of the knee energy harvester (KEH) device are as shown in Figure 4:

1. Power management circuit box.
2. Shank embedded with the inner hub
3. Inner Hub
4. Piezoelectric bimorph with attached SMs
5. Bearing
6. Outer ring
7. Stepper motor
8. Secondary magnet
9. Primary magnet

The separate components to construct the model of knee energy harvester are shown in Figure 4. This prototype model was designed using the SolidWorks software and fabricated using the High Precision Desktop 3D printer. SolidWorks is a solid modelling computer aided design (CAD) and computer aided engineering (CAE) program that runs on Microsoft Systems.

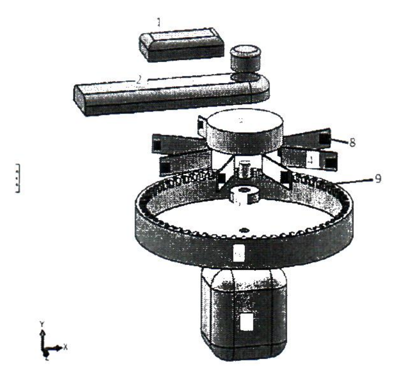

Fig. 4: Designed prototype of knee energy harvester

Piezoelectric bimorph cantilevers mounted at the inner hub were connected to the rectifier circuit. Inner hub will hold the bimorphs and be fixed to the shank. At the end of the bimorph, secondary magnets (SMs) were equally positioned and fixed. For the primary magnets (PMs), they were equally positioned and embedded along the inside of the outer ring. The number of both magnets and bimorphs depends upon the experimental requirements to make the analysis. Based on the work explored by [7, 19], the knee energy harvester featured with 8 numbers of piezoelectric bimorphs and plucked by 32 number of primary magnets (PMs) producing the highest energy output. However, for this study, the number of primary magnets used is 35 because the radius of the outer ring plate is larger.

To demonstrate the knee flexion movement in this experiment, the outer ring where the PMs were fixed, it is actuated by a stepper motor to rotate. The stepper motor is controlled by stepper motor drive A4988 and the microcontroller which is an Arduino Leonardo set as shown in Figure 5. To investigate the capability of energy harvesting, this study analyzed various parameters such as the difference number of piezoelectric bimorph used. Besides that, rotation speed of the outer ring and the angle of knee flexion affect the performance of the cantilever to generate energy. Therefore, analysis on the effect of rotation and knee flexion will be investigated too. Based on human activity, knee motion and flexion are different according to the type of activity. The speed of the motor can be adjusted by the stepper motor controller circuit and displayed by the LCD. A tachometer is used to measure the rotational speed of the outer ring. The parameters in designing the prototype must take into consideration several data such as the length and height of the bimorph cantilever, number of primary magnets and its gap. From that, the radius and the height of the outer ring can be calculated. For this prototype, the height and radius of the outer ring are 16.5mm and 51mm, respectively. The number of teeth-spacing at the edge of the outer ring purposely for installing the primary magnets is 35. The size for each teeth is 3mm cube same goes to the size of the primary magnet. For the inner ring, the height and radius are 12 mm and 19.5 mm respectively. Eight numbers of bimorph equally positioned embedded to the inner ring. The full setup of the prototype is shown in Figure 5. The setup contains all the parts which is the model of harvester, rectifier circuit, and stepper motor controller circuit.

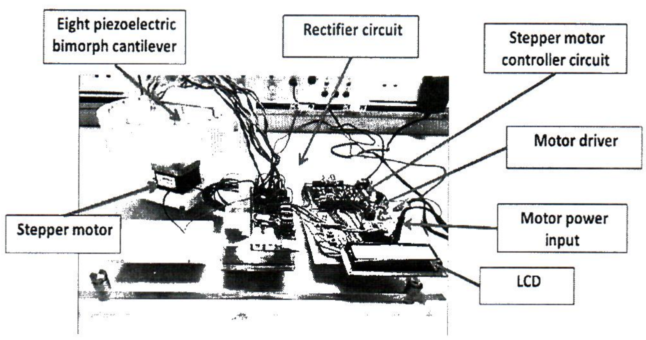

Fig. 5: Full setup prototype of knee-joint energy harvester system.

3. Results and discussion

A series of experiments were conducted on the effect of rotational speed, knee flexion angles, different number of bimorph piezoelectric module, and the method of the connection of bimorphs towards the amount of voltage and current that can be harvested.

3.1 Different number of piezoelectric bimorphs

In this section, the manipulated variable is the number of piezoelectric bimorphs used in the experiment. The fixed variable is speed of the rotation, knee flexion angle, time duration and the type of piezoelectric circuit connection. The speed of rotation is 0.386m/s with the flexion angle of 115º. The time taken for each period of experiment is 30 seconds to define the maximum, minimum and average output values. Parallel circuits are utilized in this experiment.

Based on the graph in Figure 6, it is clearly shown the trend line increases for each maximum, minimum and average voltage as the number of piezoelectric increases. After adding the number of piezoelectric modules from one to two, a rapid increase of voltage was found, followed by a continuous increment for maximum voltage, and slightly decrease for minimum and average voltage. The reason for the rapid increment is the parallel connection of piezoelectric module was set-up [4]. Next, the major peaks of voltage observed for all series samples are 12.14V, 8.67V, and 5.51 V respectively representing highest number of piezoelectric was used which is eight. Altogether, it can be seen that neither number of piezoelectric module shows a plateau voltage that indicates equilibrium results.

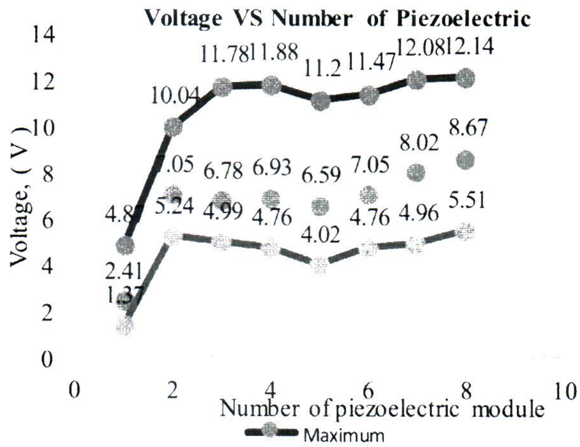

Fig. 6: Graph of voltage against number of piezoelectric bimorph

3.2 Effect of rotational speed toward energy harvested.

In this section, the objective of the experiment is to investigate the effect of rotational speed of knee flexion toward the ability of piezoelectric bimorph generate the energy. The manipulated variable is the difference rotational speed applied which is 0.237m/s, 0.282m/s, 0.334m/s and 0.386m/s. This various type of speed is to represent the difference speed of human legs gait cycle according to difference activities. The fixed variables for this experiment are angle of knee flexion, period time of collecting results and the type of piezoelectric circuit connection.

Based on the graph in Figure 7, the speed of gait cycle has the greatest influence on the amount of voltage generated. Between the speed of 0.237m/s and 0.282m/s, the generated voltage does not change too much. In that range of speed, the piezoelectric bimorph may not reach the maximum deflection which is 2mm. In view of the voltage generated at speed 0.334 m/s, a big difference observed compared at 0.282 m/s. It indicates that the piezoelectric has been deflected at its maximum range of deflection. The maximum voltage was found at the maximum speed which is 7.6 V. Besides that, from the results shown in that graph, the highest successfully generated voltage is far from the actual maximum voltage which is near to 100 V as stated in the data sheet for this type of piezoelectric module. The main cause is the bimorph does not vibrate at its resonant frequency [20].

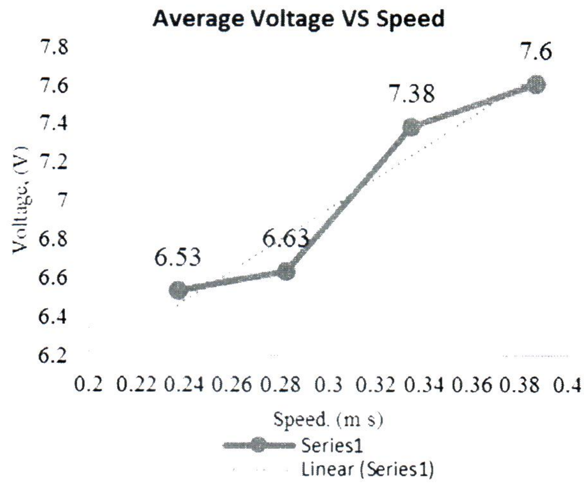

Fig. 7: Graph of average voltage against rotational speed

In graph shown in Figure 8, it is apparent that the average current generated by harvester model increased with increased rotational speed. The trend of the line seems to be linear from first speed to the third speed. After that, the rapid increase of current occurs at the highest input speed, 0.386 m/s. The total current difference between the highest and lowest speed is 0.12 mA. In general, there is no decrement of current between all differences of speed. Based on the graph shown in Figure 9, the calculated power generated increases with the increase of rotational speed. The highest power generated is 1.596 mW and lowest 0.5877 mW. When the measured voltage and current increases, the power also increases. Between the first, second and third speed, the curve of power only having a slightly increase before goes high at the highest speed. As the bimorphs hit the plectra, there is a limitation for the bimorph to freely vibrate because of the frequent contact during the rotation [21].

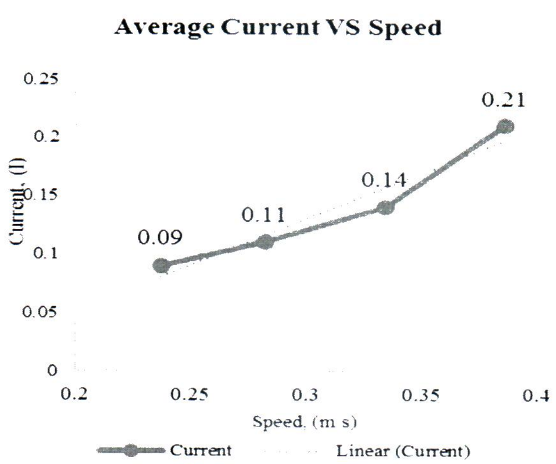

Fig. 8: Graph of average current against rotational speed

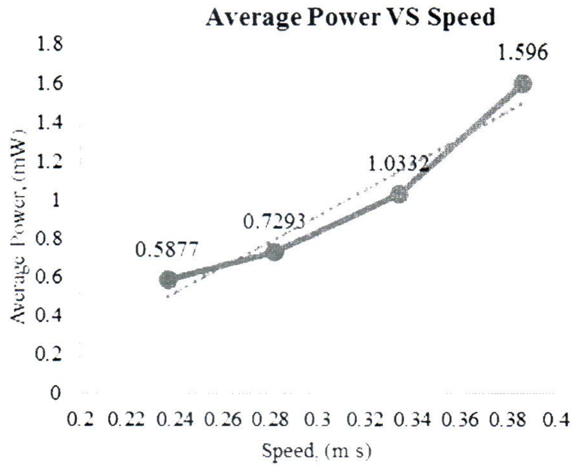

Fig. 9: Graph of average power against rotational speed

3.3 The effect of rotational angle toward energy generated.

This section is purposely to identify the effect of rotational angle towards the total energy that can be generated by the model. Constant variables for this experiment are the rotational speed of gait cycle, 0.386 m/s, numbers of piezoelectric bimorph, arrangement of rectifier circuit and the testing time with duration of 30 seconds.

From the observation of the results obtained as shown in Figure 10, the trend line for all categories of voltage is nearly the same. The trend line is almost to be flat because the voltage collected from the manipulated variable does not have much differences. The primary magnets are embedded along the outer ring. Because of that, the repulsive force between PM and SM is the same at any angle of the outer ring. For the maximum, average and minimum voltage, the percentage of voltage changes at different flexion angles are 2-3%, 1-3% and 2-10% respectively.

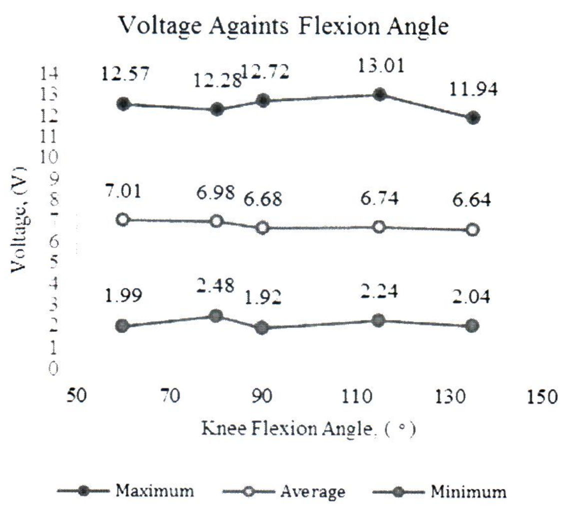

Fig. 10: Graph of voltage against flexion angle

3.4. Arrangement of piezoelectric bimorph cantilever

The purpose of this experiment is to investigate the factor of circuit arrangement towards voltage and current generated. Constant variables for this experiment are the number of piezoelectric bimorphs, and the testing time duration. Based on the graph shown in Figure 11, the current for parallel circuit shows a linear increment and is higher than the series circuit. This is due to the total current in parallel circuit is the sum of the current through each rectifier [4]. For the series connection, the voltage (data not shown) is larger, but the current is lower. The highest collected current is only 0.05 A at the highest rotational speed. To light up the LED, this type of connection is not recommended because the current is small. Less number of LED can be light up in series circuit connection compared to the parallel circuit connection.

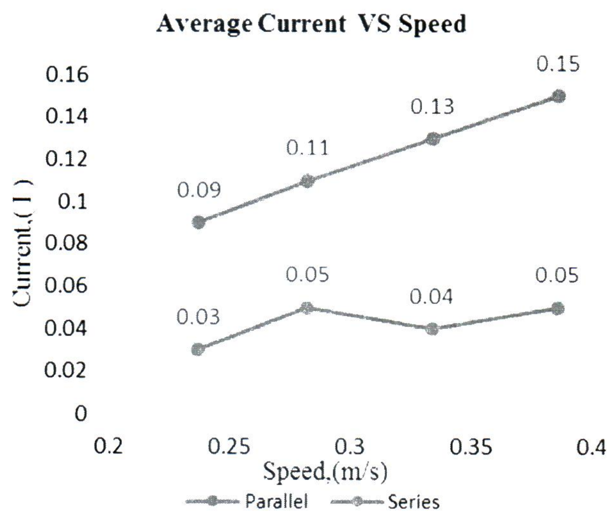

Fig. 11: Graph of average current against rotational speed

4. Conclusion

This study developed an energy harvester device by using the piezoelectric bimorph cantilever as the energy generator. The devices presented here successfully demonstrate the potential of piezoelectric energy harvesting based on the human knee joint motion. A series of experiments related to some characteristic of human knee joint motion such as speed and angle had been done to investigate the factor that affecting the ability of bimorph to generate power. For this paper, the speed used is lower than the real speed according to the types of human activities but the energy harvesting still can show the good output power. The highest power generated is 1.569 mW at the highest rotational speed, 0.386 m/s. Therefore, for the real situational speed such as 1.34 m/s for walking activity, the device absolutely can generate more power because the speed is higher. Based on the results, it can be concluded that the higher rotational speed the higher the output power. In addition, the output voltage and current also depends on the number of bimorphs used. As the number of bimorphs increases, the output has also increased. Rotational angle does not affect much to the power generated as long as the rotational speed of outer ring is constant. Finally, the same principle can be applied to other joints on the body. In general, any environment with relative movement between parts rotational can benefit from this approach.

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